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V. S. Barashenkov, K. K. Gudima and V. D. Toneyev

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MECHANISM OF INTERACTION OF FAST DEUTERONS WITH NUCLEI

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ABSTRACT. A method of calculation of inelastic collisions of deuterons with nuclei is suggested. The calculation is made by the Montecarlo method, taking into account the Coulomb and diffraction-deuteron splittings. The results of calculations agree well with the experiment.

1. Introduction

In connection with the design of high current neutron generators, and also in connection with problems of radiation shielding of spacecraft[2], the problem of learning how to calculate inelastic interactions of nuclei with nuclei at high energies has become important in recent years.

In many works, it has been shown that in the area of energies greater than a few tens of Mev, the interaction of nucleons and mesons with nuclei occurs primarily by development of an intranuclear cascade (see [3-8], where further bibliography is presented). It is extremely important to determine the extent to which this cascade mechanism is realized in the case of collisions of fast nuclei, when a very large number of interactions of the intranuclear nucleons occurs immediately. If this mechanism actually does occur, the usage of the Montecarlo method would be an /4
extremely effective method of calculating the interactions of nuclei with nuclei.

It is natural to begin a study of the interaction of nuclei with the simplest case of deuteron-nuclear collisions, especially since the greatest quantity of experimental data is available for this case.

The first such attempt was undertaken in work [8], where the Montecarlo method was used to investigate the interaction of deuterons with

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[1] Numbers in the margin indicate pagination in the foreign text.
[2] For example, see [1, 2], which contain further bibliography. Although in relation to protons the nuclear component of cosmic rays is only a few percent, the radiation effect resulting from long term space flights is determined primarily (about 80%) by this very component.

carbon at T_4 = 280 Mev[1]. The results of the calculations did not contradict the assumption of the mechanism of intranuclear cascade, although the inaccuracy of the theoretical claculation (only 80 runs were made through an extremely simplified model) and the paucity of experimental material available at the time made it impossible to produce more definite conclusions.

The usage of high speed electronic computers allows us at the present time to calculate cascades with the minimal theoretical limitations; also, a considerable quantity of experimental material has been accumulated for various targets. All of this makes it possible to produce quite unambiguous conclusions concerning the nature of the inelastic deuteron-nuclear interactions.

2. Model and Calculation Method

We will look upon the deuteron as a weakly coupled "dumbbell" system consisting of a proton and a neutron, the distance between which is fixed and equal to the mean "diameter" of the deuteron, $D = 4.3 \div 10^{-13}$ cm. The direction of the axis of the dumbbell is isotropically distributed in space, but since the orbital moment of the deuteron is equal to zero, its orientation does not change upon movement. The fixed nucleons have relative momentum p; in order to estimate the distribution of this momentum, we will use the function

$$W(p)d^3p = \frac{\hbar}{\pi \eta} \frac{d^3p}{(p^2 + \hbar^2/D^2)^3} .$$

representing the square of the Fourier component of the approximate wave function of the deuteron /5

$$\Psi(r) = \frac{1}{\sqrt{2\pi D}} \frac{e^{-r/D}}{r}$$

As calculations showed, the details of distribution $W(\overline{p})$ have little influence on the results of calculations presented below.

For the target nuclei, we will use a model of a degenerate Fermi-gas, which is usually used in calculating nucleon-nuclear cascades. In this work, we will analyze the simplest model -- the nucleus with sharp boundary

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[1] Here and throughout the following, T_4 is the kinetic energy of the oncoming deuteron in the laboratory coordinate system.

(radius $R = 1.4(?A^{1/5}?)$[1] 10^{-13} cm) and will consider that the nucleus interacts only with those deuterons whose centers of gravity pass by the center of the target nucleus at a distance of no greater than $R + D/2$. Comparison with experiments of various types allows us to determine the importance of consideration of diffusion of the nuclear boundary (we recall that in the case of nucleon-nuclear interactions, this diffusion can be ignored [4-6]).

Cases in which the target nucleus is struck by only one of the nucleons in the deuterium nucleus, while the other continues its movement practically without changing its momentum, relates to a stripping reaction; this reaction will be considered as a particular case of the inelastic deuteron-nuclear interaction and we will include its contribution in all the calculation results presented below.

However, it should be kept in mind that the stripping cross section in our calculations should be somewhat low since, due to the low binding energy of the deuteron, its splitting can also occur at the remote periphery of the nucleus, even though we are ignoring diffusion of the nuclear boundary[2].

It sometimes seems that the deuterium nucleon which strikes the /6
nucleus (both nucleons or one as occurs in the stripping reaction) passes through the nucleus without interacting; in these cases, it is believed that the deuteron did not interact with the nucleus.

In our calculations we will consider the case of elastic scattering of the oncoming deuteron from the intranuclear nucleons. In order to calculate such collisions, we use the well known experimental cross section N - d for the interactions.

Since the elastic N - d interaction cross section decreases rapidly with increasing energy, the elastic N - d scattering within the nucleus has very little influence on the results of the calculations.

We will consider that with inelastic N - d interactions, intranuclear collision (in the area of energies on the order of several hundred Mev, as we know, this is an elastic collision) occurs for only one of the deuterium nucleons, the other nucleon retaining its momentum. The further behavior

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1 The form (?...?) will be used throughout to represent the translator's guess in the frequent cases where the copy is illegible.

2 At the same time, in comparison with the well known theory of Serber [9], our calculation is more complete, since we automatically consider the possibility of stripping within the nucleus (when one of the deuteron nucleons passes through the nucleus without interaction), and we have not used the approximation $P/2R \ll 1$.

of these nucleons, like the behavior of nucleons entering the nucleus in the stripping reaction, must be analyzed within the framework of an ordinary model of an intranuclear cascade [4-6].

In order to describe the characteristics of the elastic and inelastic p-p and p-(?) interactions within the nucleus, we will use the corresponding experimental data.

All cascade calculations were performed by the Montecarlo method considering the Pauley principle and relativistic, three-dimensional kinematics; we also considered the direction of the axis of the oncoming deuteron (?and the value?) of the relative momentum of the nucleon (?in?) deuteron $\bar{p}$. The removal of the excitation of the nuclear fragment formed after the fast cascade particles leave the target nucleus was calculated within the framework of the ordinary evaporative model [7]. The results presented below are based on the calculation of approximately 2,000 runs for each target nucleus and each value of energy T_d. In some cases, for example in calculating the spectra of particles at certain angles, over 10^4 runs were calculated[1].

In addition to the processes listed above, the cross section of semielastic scattering makes a contribution also to processes of Coulomb and diffraction splitting of the deuteron. The free nucleons into which the deuteron is split in this case may then strike a nucleus and cause a nuclear reaction (one nucleon or both) or may pass by the nuclei. The first case practically does not differ from inelastic deuteron-nuclear interactions, which we described above. As concerns the second case, the cross section of the Coulomb splitting is very low ($\sigma_{Coul}/\sigma_{ln} \approx$ $\approx 10^{-(?)}(?\chi?)^{(?3?)}\%$, (?χ?) equals the nuclear charge [10, 11]) and produces a notable contribution only for heavy nuclei; the cross section of diffraction splitting on the nucleus with sharp boundary can be calculated using the formulas presented in review [11]. For heavy nuclei, it is approximately of the same order of magnitude as σ_{Coul}, while for light nuclei, it is extremely small in comparison with the cross section of inelastic interactions. /7

With the exception of cases when comparison is made to photoemulsion data, the contribution of the Coulomb and diffraction splittings thus calculated is included in all the characteristics of deuteron-nuclear interactions presented (in experiments with photoemulsions, the processes of splitting are practically not recorded; see below).

[1] The time required for one run using the M-20 computer averages 0.7 sec.

3. Results of Calculation

Table 1 shows the calculated cross sections of inelastic interactions of the deuteron with various nuclei, comparing them with the corresponding experimental quantities. The experiment and the theory are quite close to each other; however, the average experimental values (except for Al^{27}) are systematically greater than the calculated values.

As we will see below, this divergence is apparently related primarily with the particles which fly out at small angles, and (?may occur?) due to stripping type processes and the splitting of the deuteron at the remote periphery of the target nucleus, the calculation of which requires a more detailed model.

Tables 3 and 2 present the distributions of inelastic interactions by the number of charged particles produced, while Figure 1 shows the mean number of neutrons emitted as a function of the mass number of the target nucleus. The data of Table 2 characterize the cascade (shower) stage of the /8 deuteron-nuclear interaction. Table 3 and Figure 1 consider the evaporative stage as well. In the case of charged particles, fairly good agreement is observed between experimental and calculated values for both values of the density parameter (?at the level?) of the excited nuclear fragment (?) = 0.1 m (?) = 0.06 Mev^{-1}, generally used for calculation of the process of evaporation. The experimental and theoretical data on Figure 1 agree less well.

The reasons for this divergence in data for charged and neutral particles are still somewhat unclear. The divergence results partially from differences in the methods used in the experiments performed [13-15]. The photoemulsion method used in works [13, 14] for investigation of charged particles decreases the contribution of remote peripheral interactions in which the nucleus remains in the weakly excited state; these events are extremely difficult to record in the photographic emulsion, and the experimental data agree better with the cascade-evaporative model, which does not consider splitting of the deuteron. On the other hand, the method of work [15] allowed all secondary neutrons to be registered, including those formed during peripheral interactions, where their number is considerably lower than that indicated by the cascade calculations.

The fact that the divergences observed actually do result to a considerable extent from peripheral interactions is confirmed by the form of the angular and momentum distributions of secondary particles. The nucleons in inelastic collisions with large (?impact?) parameters fly out primarily in the low angular area, and it is in this very area that the calculated spectra agree poorly with the experimental curves (Figure 2); the agreement becomes worse with decreasing angle. However, the distributions produced in the photoemulsion measurements agree well with the theory (Figures 3, 4 and Tables 4, 5). Particularly indicative in this respect is the distribution shown on Figure 3c, relating to fast particles emitted at small angles $\theta \leqslant 10°$, which agrees well with the theoretical data.

Also, the usage of thick targets in turn may serve as a source of systematic errors related to the difficulty of calculating the results of these experiments per deuteron-nuclear interaction event.

Considering these factors, we must admit that the agreement between the theoretical and experimental data is quite satisfactory. /9

4. Conclusions

Thus, the cascade mechanism determines the main portion of the inelastic deuteron-nuclear interactions. The energy distribution of the nucleons generated is characterized by a peak in the area $T = T_d/2$. The particles driven out of the nucleus by the fast deuteron are strongly collimated in the direction of movement of the deuteron. Upon transition to heavier nuclei, the angular distribution of the fast nucleons is broadened, which is related to a large number of intranuclear interactions.

In contrast to the interaction of nucleons with nuclei, in the case of deuteron-nuclear interactions the diffusion of the nuclear boundary is quite essential. If this diffusion is not taken into consideration, only the mean characteristics will agree with the experimental data; all quantities relating to the small angle area will be artificially reduced.

TABLE 1. CROSS SECTIONS OF INELASTIC DEUTERON-NUCLEAR INTERACTIONS σ_{ln} at T_d = 180 Mev (in barns)

Nucleus	Experiment [12]	Theory A	Theory B
Al^{27}	0,966 ± 0,05	0,96 ± 0,02	1,04 ± 0,02
Ca^{53}	1,76 ± 0,17	1,53 ± 0,03	1,64 ± 0,03
Ta^{181}	3,13 ± 0,30	2,70 ± 0,05	2,[illegible] ± 0,05
Pb^{207}	3,44 ± 0,17	2,85 ± 0,06	3,10 ± 0,06
Bi^{209}	3,55 ± 0,18	[illegible] ± 0,06	3,15 ± 0,06
U^{235}	3,81 ± [illegible]	3,13 ± 0,07	3,41 ± 0,07

A -- cross section of cascade interactions calculated by Montecarlo method;
B -- complete cross section of inelastic interactions in consideration of Coulomb and diffraction splitting (on nucleus with sharp boundary).
Errors in theoretical values purely statistical.

[redacted]

TABLE 2. DISTRIBUTION BY NUMBER OF FAST PROTONS (WITH ENERGY $T_p > 50$ Mev) IN TRACES FORMED IN PHOTOEMULSION BY 275 Mev DEUTERONS (%)

Number of protons	Experiment [13]	Theory
0	47.9±3.5	45.8±3.4
1	46.8±3.5	50.3±3.6
2	5.3±1.1	3.9±1.0

TABLE 3. DISTRIBUTION BY NUMBER OF RAYS IN BURST TRACK FORMED BY DEUTERONS IN PHOTOGRAPHIC EMULSION (%)

	T_d = 220 Mev			T_d = 275 Mev (?)		
No. of rays	Experiment [14]	Theory[1] A	Theory[1] B	Experiment [13]	Theory A	Theory B
0	-	6.0±0.5	5.0±0.5	23.5±5.3	10.4±0.7	7.4±0.6
1	12.8±9.9	22.4±1.0	21.0±1.1	21.2±5.0	15.8±0.9	17.C±1.0
2	33.2±1.5	29.9±1.9	26.5±1.8	22.4±5.1	17.5±1.0	23.4±1.1
3	22.0±1.2	23.8±1.5	22.2±1.1	16.5±4.4	22.5±1.1	18.0±1.0
4	16.5±1.0	14.2±1.0	15.9±1.0	9.4±3.3	17.5±1.0	15.5±0.9
5	10.5±0.8	6.7±0.5	8.5±0.6	4.7±2.3	10.0±0.7	11.0±0.7
6	3.0±0.5	2.1±0.3	3.7±0.4	2.3±1.6	4.5±0.4	5.2±0.4
7	2.0±0.4	0.6±0.1	1.5±0.2	0	1.3±0.2	1.6±0.2
8	0	0.3±0.1	0.7±0.1	0	0.5±0.1	0.6±0.1
9	-	-	-	0	0	0.3±0.1

Cases A and B calculated for level density parameters (?) = 0.1 and (?) = 0.05 Mev^{-1} respectively.

[1] In work [14], events in which only neutral particles were formed were not taken into consideration; therefore, the theoretical distributions were normalized for the complete number of events recorded with (?) > 0.

TABLE 4. WIDTH OF ANGULAR DISTRIBUTION OF NEUTRONS FORMED DURING INTERACTION OF DEUTERONS WITH VARIOUS NUCLEI AT ENERGY T_d = 190 Mev.

Z = atomic number of target nucleus

Z	θ(?1/2?))°) Theory	Experiment[1]
13	9.0±1.5	9.3±0.5
73	11.5±1.5	11.4±0.5
82	11.6±1.5	11.7±0.5
92	12.6±1.5	12.0±0.5

[1] The values presented here correspond to line $\theta_{(?1/2?)}$ = 180/(?) (0.155 + 0.0006÷Z), approximating the experimental data in work [17].

TABLE 5. ENERGY DEPENDENCE OF ANGULAR DISTRIBUTIONS OF CHARGED PARTICLES FORMED UPON BOMBARDMENT OF PHOTOGRAPHIC EMULSION WITH DEUTERONS WITH ENERGY T_d

$$w(\theta) = \int_{\theta_1}^{p_2} N(\theta)\, d\cos\theta \Big/ \int_{0}^{w} N(\theta)\, d\cos\theta$$

$\theta_1-\theta_2$	T_d = 35 Mev Experiment [18]	T_d = 35 Mev Theory	T_d = 80 Mev Experiment [18]	T_d = 80 Mev Theory	T_d = 130 Mev Experiment [18]	T_d = 130 Mev Theory	T_d = 100 Mev Experiment [18]	T_d = 100 Mev Theory
0-30	37.0±2.0	57.7±2.9	36.2±2.0	42.7±2.1	33.7±1.9	35.2±1.7	29.4±1.8	30.8±1.5
30-90	43.7±2.2	28.4±1.4	39.7±2.1	36.4±1.8	38.5±2.1	42.4±2.1	42.7±2.2	45.0±2.2
90-150	14.5±1.3	11.9±0.6	18.0±1.4	15.2±0.7	21.0±1.5	16.3±0.8	20.6±1.5	17.7±0.9
150-180	4.8±0.7	2.0±0.1	6.1±0.8	5.7±0.3	6.8±0.9	6.1±0.3	7.3±0.9	6.5±0.3

The theoretical data presented relate to (?) = 0.1; within the limits of statistical error, they correspond to the values for (?) = 0.05. Where T_d = 35 Mev, the calculation is significant only as an estimate, since the energy of the deuteron nucleons in this case is only about 12 Mev; still, the difference between theoretical and experimental data is not too great.

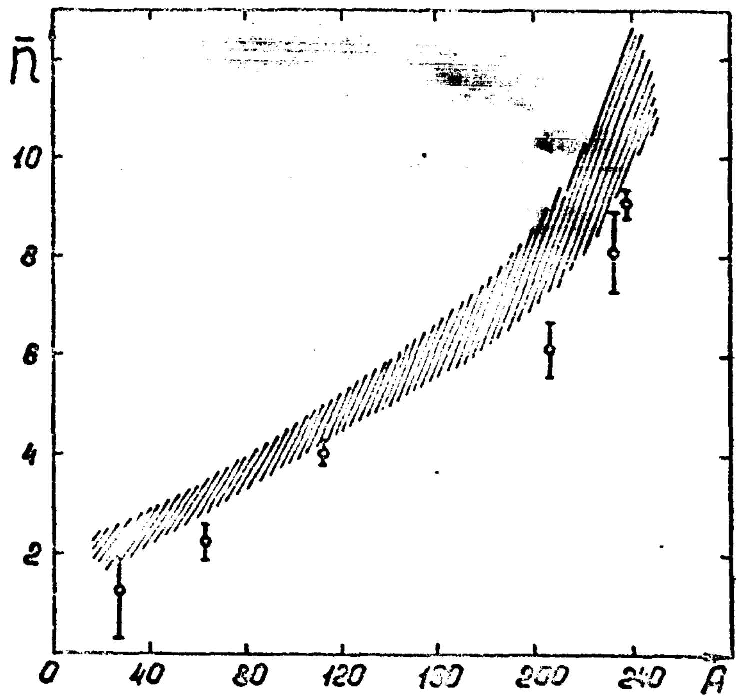

Figure 1. Mean Number of Neutrons Formed in Inelastic Deuteron-Nuclear Interaction at T_d = 180 Mev. A, Mass number of target nucleus. Shaded area corresponds to values calculated for parameters of level densities 0.1 $Mev^{-(?)}$ ⩾ ⩾ (?) ⩾ 0.08 Mev^{-1} (considering Coulomb and diffraction splitting.

The experimental points presented are from workm[15], and relate to the primary beam of deuterons with energy T_d = 180 Mev. However, due to the ionization losses in the thick target used in work [16], deuteron-nuclear interactions occur at T_d = 180 Mev.

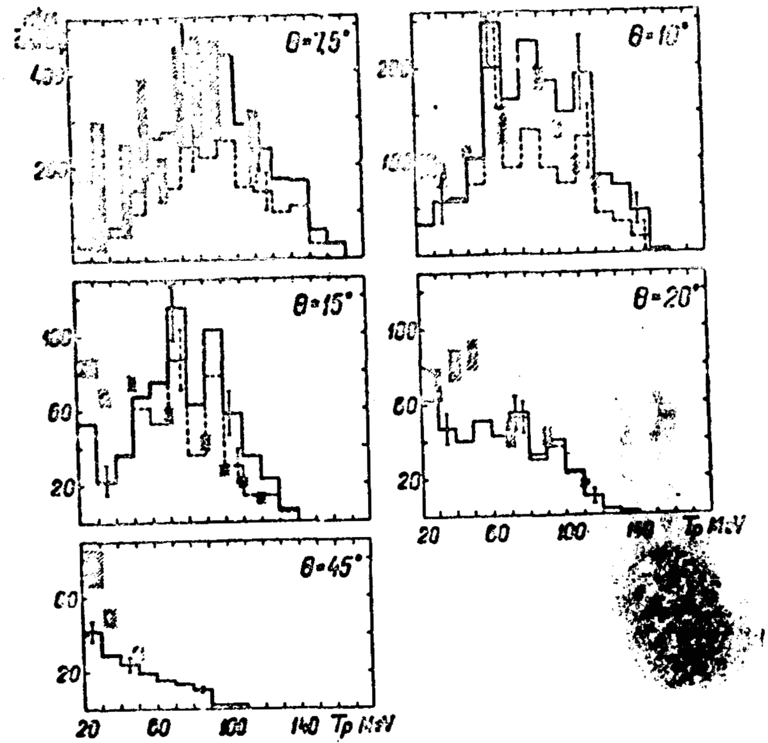

Figure 2. Energy Spectrum of Protons Formed Upon Interaction of 180 Mev Deuterons with U^{238} Nucleus. θ -- proton emission angle in laboratory system of coordinates. Dotted line -- results of cascade calculation; the solid curve additionally considers the contribution of the processes of deuteron splitting in the approximation with the sharp U^{238} nucleus boundary. The shaded area shows the error in the experimental data [16].

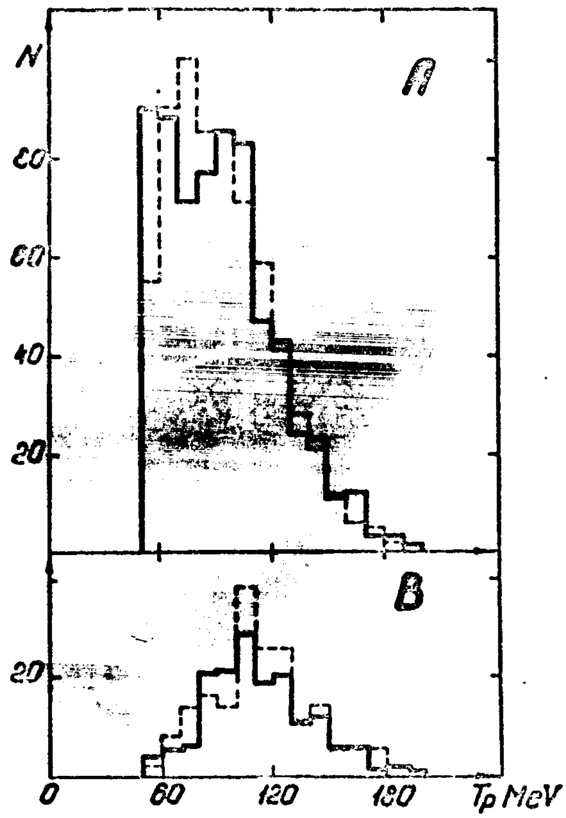

Figure 3. Energy Spectrum of Fast Protons Formed upon Interaction of 220 Mev Deuterons with Photoemulsion. A, all protons with energies $T_p > 50$ Mev; B, Protons with $T_p > 50$ Mev emitted at angles $\theta \leqslant 10°$. Solid curve, calculation for average nucleus of photoemulsion Ca^{70}; dotted line, experimental data from work [14].

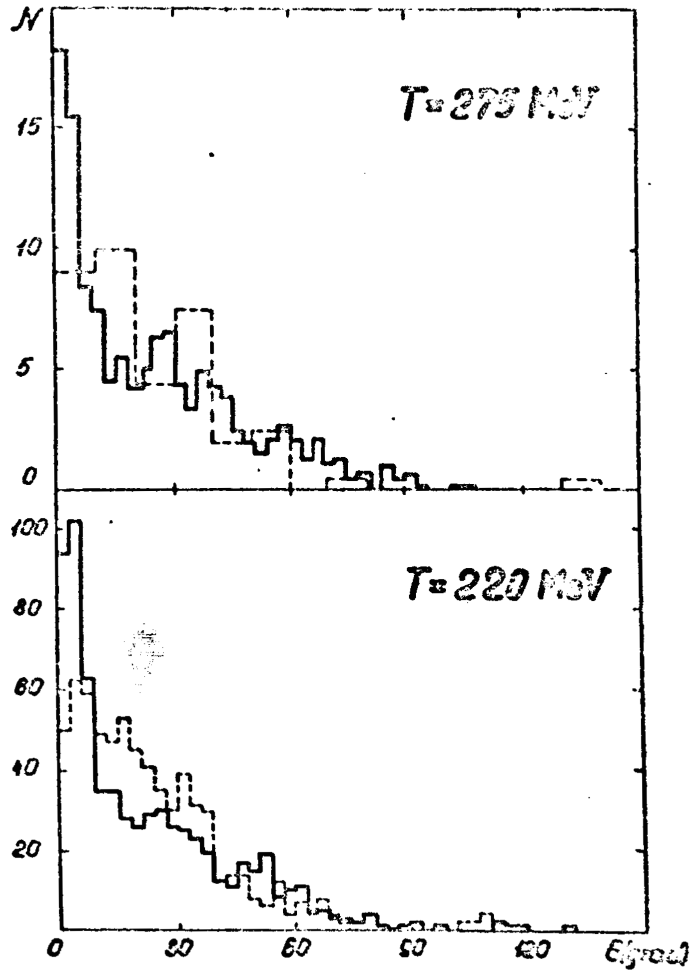

Figure 4. Angular Distribution of Fast Protons (T_p > 50 Mev) Formed upon Bombardment of Photoemulsion by Deuterons. Solid curves, calculation for average photoemulsion nucleus Ca^{70}; dotted line, experimental data from works [13, 14].

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